Performance of a New Schottky CdTe Detector for Hard X-ray Spectroscopy

C. Matsumoto[1,2], T. Takahashi[1], K. Takizawa[1], R. Ohno[3], T. Ozaki[3] and K. Mori[4]
[1]Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan
[2]Department of Astronomy, the University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
[3]ACROTEC, Japan Energy Corporation, 3-17-35, Niizo-Minami, Toda, Saitama 335-8502, Japan
[4]CLEAR-PULSE Company, Ltd., 6-25-17, Chuo, Ohta, Tokyo 143-0024, Japan

Abstract

We report a significant improvement of spectral properties of a cadmium telluride (CdTe) detector. This was accomplished via the use of a high quality CdTe crystal, where high Schottky barrier for the holes on a CdTe surface was formed by using a low work-function metal, indium. With a 2×2 mm^2 detector at a thickness of 0.5 mm, the leakage current is measured to be 0.7 nA at room temperature (20 °C) and below 1 pA at -70 °C for 400 V bias voltage. The low leakage current allows us to operate the detector at a higher bias voltage than for previous CdTe detectors. The energy resolution we achieved at room temperature is 1.1–2.5 keV FWHM from the energy range of 2 keV to 150 keV at 20 °C without any charge-loss correction electronics. At -70 °C, we obtained an energy resolution of 1.0 keV FWHM at 122 keV and 2.1 keV FWHM at 662 keV.

I. Introduction

Cadmium telluride (CdTe) has been regarded as a promising semiconductor material for X-ray and γ-ray detectors operated at room temperature, because of its features such as a high atomic number ($Z_{Cd} = 48, Z_{Te} = 52$) and a large band gap energy ($E_g \sim 1.5$ eV) [1]. However a considerable amount of charge loss in CdTe has limited its capability when such detectors are used as high resolution spectrometers required in X-ray and γ-ray astronomy.

This problem is due mainly to the relatively poor charge transport property of holes (mobility-lifetime product: $\mu\tau \sim 10^{-5}$–10^{-4} cm^2/V) compared to that of electrons ($\mu\tau \sim 10^{-4}$–10^{-3} cm^2/V). In order to collect all charge carriers created in the CdTe detector, a bias voltage of several thousand V/cm is required. Without sufficient voltage, the pulse height depends on the interaction depth [2, 3]. In a semiconductor device, the magnitude of the electronic noise strongly depends on the leakage current because the low-noise charge-sensitive amplifier integrates the charge in the crystal and converts it to a voltage pulse. Therefore, the suppression of the leakage current is an important factor in achieving high energy resolution.

Commercially available CdTe detectors use high work-function metal such as Au or Pt to form ohmic contacts. According to Iwase et al. [4], the leakage current of the Pt/CdTe/Pt electrode system is explained by the hole injection from the positive electrode (anode). The low Schottky barrier height for the holes at the metal/p-CdTe results in large leakage current when we apply high bias voltage, which is necessary to obtain useful electric field for the collection of charges. Although this electrode system shows long term stability, the spectral performance is far from superior.

Great efforts have been made to form a high Schottky barrier with a low work function metal such as Al or In (indium) [5, 6], but the lack of stability and relatively poor energy resolution have limited the usefulness of this type of CdTe detectors in the past. Squillante et al. [7] reported promising results from In/CdTe/Pt and In/CdTe/Au electrode systems in conjunction with the rise time discrimination electronics. Recently Ozaki et al. [8] found that the leakage current is significantly suppressed with the use of In as a positive electrode when they use high quality CdTe material produced by ACROTEC [9]. After careful thermal treatment and the selection of proper crystal orientation for the electrode system, they succeeded to obtain a good performance in the current mode operation. In this paper we demonstrate the performance of the new Schottky CdTe detector at or below room temperature in the energy range from 2 keV to ∼700 keV.

II. Schottky CdTe Detector

The Schottky CdTe detectors used in this study were fabricated with the prescription described in Ozaki et al. [8]. We used Cl-doped CdTe single crystal grown by the traveling heater method (THM). It has p-type resistivity of $\rho = 4 \times 10^9$ Ω cm. The $\mu\tau$ products are $\sim 10^{-4}$ cm^2/V and $\sim 3 \times 10^{-3}$ cm^2/V for holes and electrons, respectively. The polished wafers with (1,1,1) orientation were evacuated and heated up to 200–300 °C to remove the Te-rich amorphous layer. A Schottky junction was formed by evaporating In on the Te-face of the wafer; the ohmic contact by Pt was formed on the opposite face by electroless plating (In/CdTe/Pt electrode system). The wafers were then cut into detectors and mounted on Alumina backing. The detector used in this study has an effective area of 2×2 mm^2 and a thickness of 0.5 mm. For comparison, we prepared a detector with the Pt/CdTe/Pt electrode system (hereafter we refer to it as Pt/CdTe/Pt).

III. Current-voltage Characteristics and Hole Transport Property

A. I-V characteristics

In the Schottky CdTe detector, the positive bias has to be applied on the In electrode. The current–voltage characteristics of the Schottky CdTe detector and the Pt/CdTe/Pt are shown in Fig. 1 at different operating temperatures. The leakage current of the Schottky CdTe (reverse current) is much more reduced than that of Pt/CdTe/Pt ($\sim$ 2 orders of magnitude at 100 V). Even at room temperature (20 °C), the leakage current was suppressed to 0.7 nA at a bias voltage (V_B) of 400 V. By cooling to -10 °C, the leakage current decreased to 100 pA even at 700 V bias. At -70 °C, the leakage current further decreased below 1 pA, which is too low to be measured by our instruments.

Using the measurements at metal/n-CdTe interface using the CdTe crystal by ACROTEC [4, 10], the Schottky barrier heights at In/p-CdTe and Pt/p-CdTe are calculated to be 1.38 eV and 0.53 eV, respectively. The significant suppression of the leakage current for the In(anode)/CdTe/Pt(cathode) implies that the barrier height at the anode surface is high enough to prevent the injection of holes into CdTe.

B. Hole Transport Property

For full charge collection in the detector, the required bias voltage is calculated to be 500 V for the 0.5 mm thickness from the $\mu\tau$ product of holes. In order to see the improvement of the hole transport property with respect to the bias voltage, 5 MeV α particles from ^{241}Am source are directed onto the positive electrode. Since α particles stop at the surface of CdTe, the pulse observed at the output of the charge sensitive amplifier (CSA) is from the transit of holes across the CdTe detector. In the measurement, we use the CSA (ORTEC 142A) with a capability of measuring fast rise times up to 10 ns.

As shown in Fig. 2, the hole rise time becomes shorter when we applied higher bias voltage. The rise time of holes at V_B=80 V and at V_B=700 V is 400 ns and 40 ns, respectively. At 700 V operation, the measured rise time corresponds to a hole velocity of 1.3$\times$10^6 cm/s. It should be noted that, with this fast rise time, we are able to use the detector in a high counting environment of $\sim$ 1 MHz. Fig. 2 also shows that the amplitude of the pulse at V_B=80 V increases about 10–20 % when we apply V_B=700 V. This shows that the high bias voltage, i.e, the high carrier velocity, is effective to improve the charge collection efficiency.

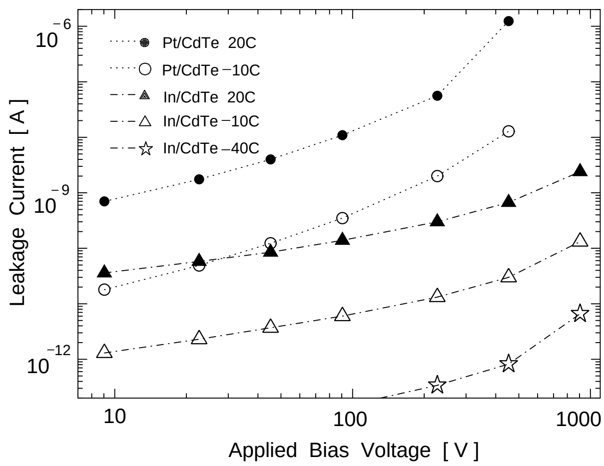

Figure 1: Current – voltage (I-V) characteristics of the Schottky CdTe and the Pt/CdTe/Pt at different operating temperatures. Each detector has a dimension of 2$\times$2 mm^2 and a 0.5 mm thickness. In the Schottky CdTe, the positive bias was applied to form Schottky barrier for holes at In/p-CdTe interface.

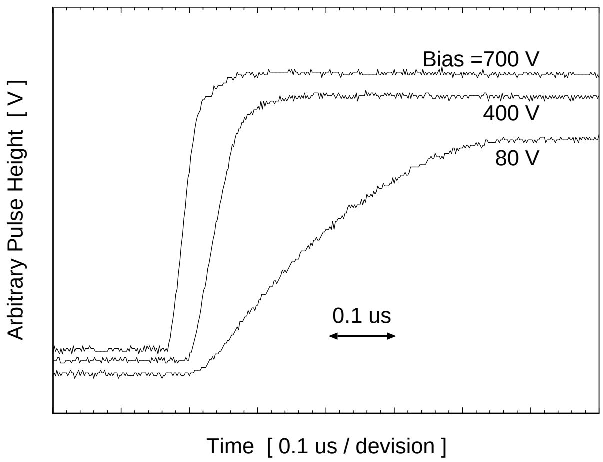

Figure 2: Pulse profiles at the output of a charge sensitive amplifier (ORTEC 142A) for α particles (E_α =5 MeV) on the positive electrode. The pulses represent hole traversal in the CdTe with a thickness of 0.5 mm. Increasing the bias voltage decreases the hole rise time. At 700 V (equivalent electric field of 14 kV/cm), the amplitude of the pulse almost reached that expected for full charge collection. The detector is operated at 20 °C.

IV. Spectral Performance

A. Experimental Setup

The extremely low leakage current of the Schottky CdTe detector requires a careful design of a Charge Sensitive Amplifier (CSA) to obtain the best performance. The input capacitance (C_{in}) of the detector and the connector is measured to be about 2 pF. Special care was taken to select FETs with a low gate leakage current. The feedback network consists of 0.5 pF capacitance and 10 GΩ resistance [11]. The charge signal is integrated in the CSA and shaped by an ORTEC 571 amplifier. With 2 μsec shaping time, the equivalent noise charge was 0.85 keV at $C_{in} = 0$ pF and 1.35 keV at $C_{in} =$ 30 pF, respectively. We mounted the detector and the CSA into the thermostatic chamber with the temperature controlled from 20 °C to -70 °C.

In order to minimize the effect of the incompleteness of the hole collection, we irradiated γ-rays from radioactive sources on the negative electrode (cathode). For low-energy γ-rays which interact near the cathode, most of the signal to be integrated by the CSA is due to the transit of electrons. Throughout the experiment, we did not use rise-time discrimination or pulse-height correction electronics.

B. Performance at Room Temperature (20 °C)

The low leakage current and the fast hole transport property of the Schottky CdTe detectors are good indications to that for fine spectroscopy. **Here is now under construction.**
Figure 3 shows the energy spectrum of γ-rays from ^{241}Am obtained at 20 °C by the Schottky CdTe detector and Fig. 4 shows that by the Pt/CdTe/Pt. The improvement of the energy resolution is clearly seen by a comparison of the two spectra.

The applied bias voltage was determined such that the reasonable lowest threshold energy (several keV) was obtained. This criterion corresponds to the bias voltage of 400 V for the Schottky CdTe and 40 V for the Pt/CdTe/Pt. The best energy resolution was obtained when the time constant of a shaping amplifier was set at 0.5 μs for both detectors. The electronic contribution of the leakage current and the detector capacitance of $\sim$4pF (including male/female BNC connectors) were measured by injecting signals from a pulser. The broadening of the test pulse was 1.1 keV FWHM for the Schottky CdTe and 1.7 keV FWHM for the Pt/CdTe/Pt.

The effect of high bias voltage is shown in the shape of the 60 keV line in Fig. 4. Since the 40 V bias for the Pt/CdTe/Pt is far from sufficient for the full charge collection for 60 keV γ-rays at 0.5 mm CdTe thickness, the low-energy tail due to charge trapping is observed.

Figure 5 shows the energy spectrum of ^{57}Co obtained for the Schottky CdTe with the same operating condition. The 6.4 keV line is clearly resolved from the noise. The energy resolution of the 14 keV line is 1.2 keV FWHM. The lowest threshold of the spectrum due to noise is $\sim$ 2 keV. Since the absorption length for 122 keV γ-rays in CdTe (2 mm) is longer than the thickness of the detector, the near-symmetric shape for the 122 keV line indicates that the full charge collection is almost complete by the 400 V bias operation.

C. Performance at Low Temperature

The decrease in detector leakage current introduces dramatic improvements on the spectrum when we cool the detector. Also the electronic noise of the CSA is expected to be reduced in the low temperature operation. By cooling down the detector below -10 °C, the best energy resolution was obtained at 2 μs shaping time.

The energy resolution of the 14.4 keV line for ^{57}Co improved to 0.9 keV at -10 °C (V_B = 700 V). In order to apply much higher bias voltage, we cooled down the detector to -70 °C (Fig. 6) and operated at V_B = 1400 V. As shown in this figure, the energy resolution for the 14.4 keV line becomes 0.7 keV FWHM. Fe K-α (6.40 keV) and K-β (7.06 keV) lines are beginning to be resolved. The bias voltage of 1400 V corresponds to $\sim$ 30 ns crossing time between electrodes for holes, which is shorter by more than an order of magnitude than the hole lifetime (τ $\sim$ 1 μs). At this electric field (28 kV/cm), the line shape of 122 keV and 136 keV do not show any broadening.

In order to study the spectral performance for higher γ-ray lines, we irradiated the detector with ^{137}Cs using the same operating conditions. The energy resolution of 2.1 keV FWHM

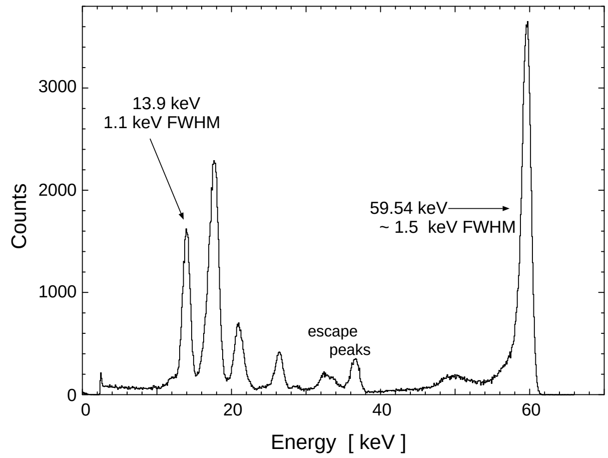

Figure 3: ^{241}Am spectrum obtained by the 2× 2 mm^2 Schottky CdTe detector with 0.5 mm thickness at 20 °C. Positive bias of V_B = 400 V was applied on the In electrode (anode). The shaping time was 0.5 μs. It should be noted that any rise time discrimination or pulse height correction electronics was not used.

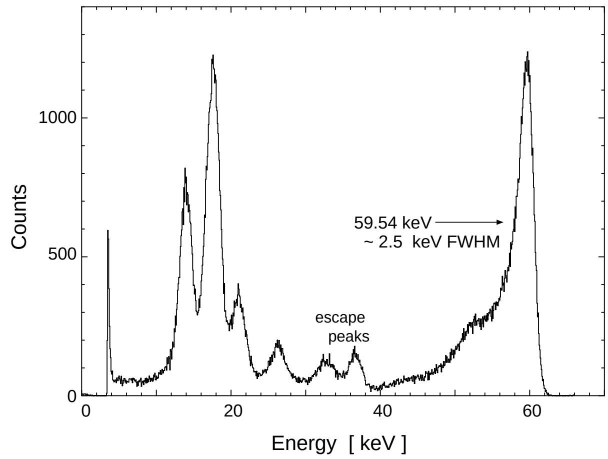

Figure 4: ^{241}Am spectrum by the Pt/CdTe/Pt detector at 20 °C under operating condition of 40 V bias and 0.5 μs shaping. The detector has same dimensions as that of the Schottky CdTe. The low energy tail because of incomplete charge loss due to trapping is clearly seen.

is obtained for the 662 keV line (Fig. 7). In the previous experiments, measurements of energy of γ-rays above 500 keV were usually obtained with the help of electronics, which correct the charge loss using the rise time information or select events with fast rise time [3]. The Schottky CdTe, with a thickness of 0.5 mm and under high bias voltage, does not require such electronics even for the 662 keV photons.

D. Long Term Stability

The long term stability is one of the key issues for the practical use of the detector. We studied the stability of the Schottky CdTe detector with different operating temperatures and bias voltages. Figure 8 shows the stability obtained by one of the Schottky CdTe detectors under different operating conditions. We found that under the operation at 20 °C and 400 V bias, the spectral performance was stable for 2-3 hours.

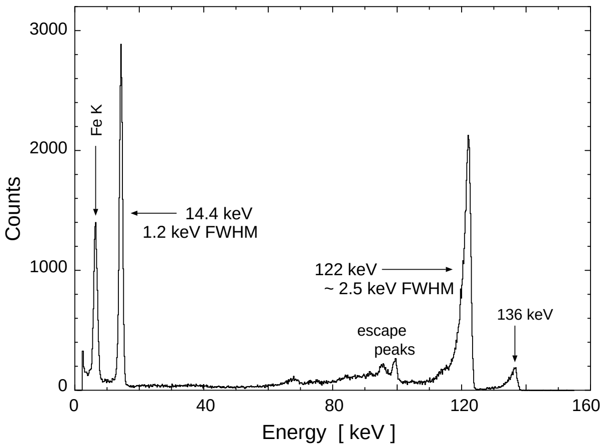

Figure 5: The room temperature (20 °C) ^{57}Co spectrum obtained from the Schottky CdTe. The 6.4 keV Fe-K line is clearly resolved.

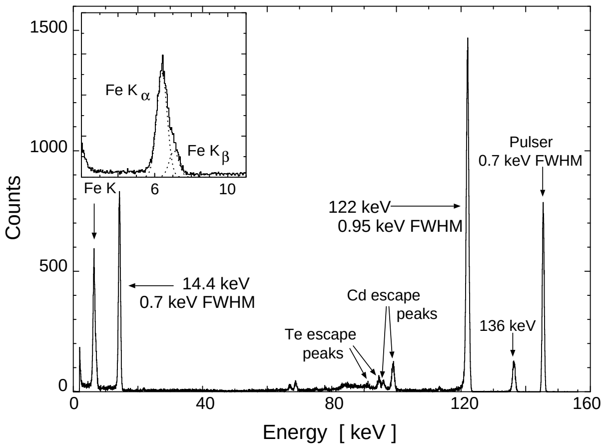

Figure 6: ^{57}Co spectrum obtained with the Schottky CdTe at -70 °C without any pulse-height correction. Applied bias voltage was 1400 V. No low-energy tail is seen for all γ-ray lines. Thus, we achieved 1.0 keV FWHM resolution even at 122 keV. Complex escape peaks can be seen at around 95 keV. The most intensive one is identified as Cd K-α escape peak. The insert illustrates the blow-up around Fe K lines. The dotted lines shows a model consisting 2 Gaussians that correspond to Fe K-α and K-β lines.

We measured the shift of the peak and the gradual increase of the low-energy tail, especially at high energy band. These phenomena are similar for those reported as "Polarization" in the literature[5, 12]. At $V_B = 200$ V, the degradation of the spectrum started after ~ 30 min. It should be noted that the spectral performance recovered after the bias voltage was re-applied.

At $V_B = 400$ V and -10 °C, the detector performed consistently for several days. The polarization effect is probably due to the charge accumulation by the non-uniform electric field in the CdTe detector [13]. Our results imply that the effect can be overcome by applying a high bias voltage and/or operating at a low temperature. A detailed study about this phenomena in the Schottky CdTe detector is now underway.

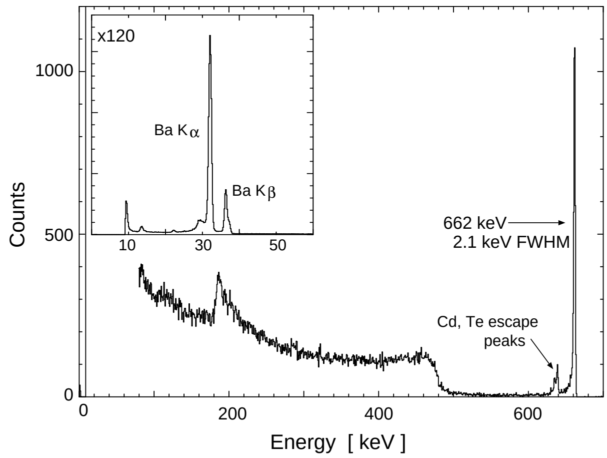

Figure 7: ^{137}Cs spectrum obtained by the Schottky CdTe at -70 °C without any rise time discrimination or pulse height correction electronics. All operating conditions are same as Fig. 6. The insert illustrates the ^{137}Cs spectrum in the low energy region. Two lines from Ba produced by successive decay are seen.

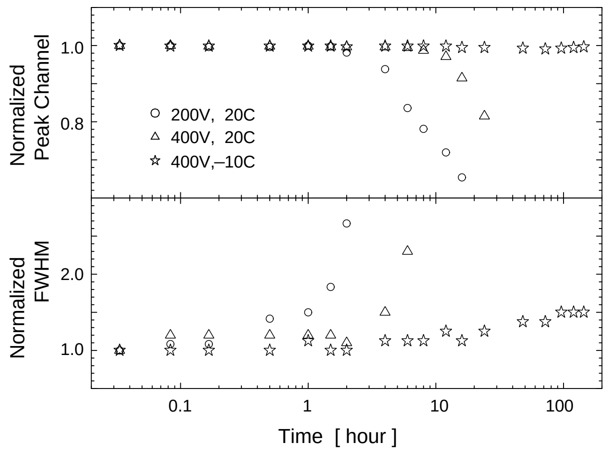

Figure 8: Stability of the spectral performance of the Schottky CdTe detector at different operating conditions. Horizontal axis shows the time in hours after the bias was applied on the detector. Top and bottom panels show the relative change of the peak channel and the energy resolution (FWHM) of the ^{57}Co 122 keV line, respectively. Data are normalized by the value at the time when the bias was ON. Some differences were observed among several samples.

V. CONCLUSIONS

We investigated the Schottky CdTe detector with the In/CdTe/Pt electrode system using a high quality CdTe crystal manufactured by ACROTEC. Good performance was obtained at room temperature operation. We achieved an energy resolution of 1.1–2.5 keV FWHM at 20 °C in the energy range from ∼2 keV up to ∼150 keV without any charge loss correction or rise time discrimination electronics. The energy resolution improved to ~ 1.0 keV FWHM when we cooled the detector to -70 °C. This recent improvement of performance was achieved by: (1) recent progress of crystal fabrication method at ACROTEC, (2) high Schottky barrier for holes formed at In/p-CdTe interface, and (3) the development of low-noise charge sensitive amplifiers specially designed for the low-leakage-current detector.

We confirmed that, once high electric field of several kV/cm is applied, the Schottky CdTe has a very good energy resolution as well as the stability to be used for a practical application.

VI. Acknowledgments

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VII. References

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